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Aerobic solid-state fermentation of the solid fraction of pig slurry

R. Uvarov*, E. Shalavina, A. Briukhanov and E. Vasilev

Federal State Budgetary Scientific Institution “Federal Scientific Agroengineering Center VIM”, 3, Filtrovskoje Shosse p.o. Tiarlevo, RU196625 Saint Petersburg, Russia
*Correspondence: puo-24@mail.ru

Abstract. Current expansion in the pig number in Russia and their concentration in separate locations contribute to higher environmental risks. One key risk factor is the slurry produced. To utilize it more efficiently, many pig farms introduce its solid-liquid separation. The study objective was to explore the feasibility of accelerated aerobic solid-state fermentation of the solid fraction of pig slurry in closed installations. The stable thermophilic process under the temperature above +55 °C achieves shorter processing time of 3–4 days. To date, however, there is no representative evidence of such an experience. Four options of fermented mixture composition were tested based on two types of the solid fraction of pig slurry: Type 1 fraction coming from a screw separator and Type 2 fraction coming from a decanter centrifuge. The fermenter operating modes were tested in the authors’ previous studies associated with processing of the solid fraction of cattle manure and bedding poultry manure. The intensity measure of fermentation was the temperature reached by the processed material in the fermenter. Under the investigated operation modes, the stable temperature was observed for nine days in the mesophilic process: 20 °C to 55 °C; in some cases, the transition to the thermophilic process – above 55 °C was recorded. Adding the catalytic components to the processed material accelerated the substrate self-heating and a higher temperature up to 59 °C was reached. This suggests that the considered operating modes of the fermenter were suitable for the fermentation of the specified substrate.

Key words: solid-state fermentation, aerobic fermentation, pig slurry, slurry handling.

INTRODUCTION

Ensuring food security is one of the top priorities for global economic development. The Baltic Sea Region, which includes Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia (Northwestern Federal District), and Sweden, is one of the most economically developed regions in the world. With a population of above 45 million people (Eurostat, 2018; DYR, 2018), the Baltic Sea Region provides about 30% of European trade (Kivikari & Antola, 2004; Studzieniecki, 2016). Highly developed agriculture is to be in place to supply such a population with the sufficient quantity of food products of proper quality.

As the Northwestern Federal District of the Russian Federation has the cool temperate climate and humus-poor soils, it falls within the zone of risky crop farming thus making the animal husbandry the main agricultural sector. For example, the gross volume of livestock products here is three to four times higher than that of crop products (Briukhanov, 2017).

Pig farming is one of the most dynamic agricultural sectors in the region. In particular, in Russia, from 2010 to 2018, the number of pigs in the Baltic Sea catchment area increased from 463.4 to 1704.6 thousand head, and in the whole country – from 17251.4 to 23726.6 million head (UIISS, 2018). Such significant growth has been underpinned by the production increase and intensification. In the pig industry in 2010, the 20 largest producers accounted for 49.2% of all pork produced in the country. By 2018, this value amounted to 65% (NPFU, 2011; NPFU, 2019).

Higher pig stock and its concentration in particular locations bring, however, the challenge of waste utilization to the next quality level. The current trend to solid-liquid slurry separation on the large-scale pig complexes promotes the search for new, more intensive and environmentally friendly slurry utilisation technologies. Several studies have verified the inverse relationship between the moisture content of the resulting organic fertiliser and its nutritional value and effective transportation distance (Vasilev, 2014; Briukhanov et al., 2017; Uvarov et al., 2018; Sharma et al., 2019).

Aerobic solid-state fermentation has proved to be an efficient method of various organic waste processing including a solid fraction of animal/poultry manure. The closed-type fermenters minimize the impact of the external weather factors, such as precipitation, the outdoor air temperature and humidity, etc. This has a positive effect on the nutrient loss, the end-product quality and the processing time, reducing it to several days (Leach, 2015; Uvarov et al., 2016; Fournel et al., 2019).

Currently, the aerobic solid-state fermentation of pig slurry is less investigated compared to other waste, cattle and poultry manure in particular. The literature survey did not reveal sufficient data on the mesophilic and thermophilic processes of the set intensity in the pig slurry. Therefore, the study objective was to explore the possibility of accelerated processing of the solid fraction of pig slurry in a fermenter.

MATERIALS AND METHODS

The study had two steps. Step 1 explored the possibility of accelerated processing of separated solid fraction of pig slurry. Step 2 identified the composition of the fermentable substrate based on the solid fraction of pig slurry, which provided the required intensity of the aerobic solid-state fermentation. With this aim in view, two types of the solid fraction of pig slurry were supplemented with grain mechanical cleaning waste, water and BIAGUM – an organic fertiliser produced from the bedding poultry manure after the aerobic fermentation. The optimal ratio of substrate components was determined with due account for the restrictive values of the above-considered criteria by the formula (1):

$$X_{i\,a} = \frac{M_I \cdot X_{i\,I} + M_{II} \cdot X_{i\,II} + M_G \cdot X_{i\,G} + M_W \cdot X_{i\,W} + M_B \cdot X_{i\,B}}{M_I + M_{II} + M_G + M_W + M_B} \qquad (1)$$

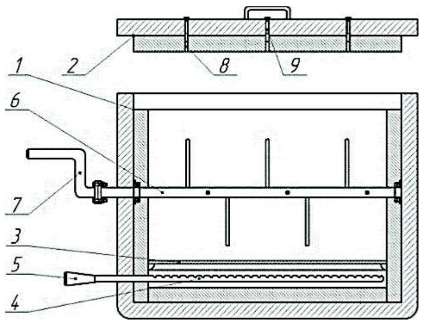
where $X_{i\,a}$ – actual (measured) value of the i-th parameter of the substrate (*W, pH, C/N*) with the standard deviation; M_I – calculated mass of Type 1 fraction, kg; $X_{i\,I}$ – actual (measured) value of the i-th parameter of Type 1 fraction; M_{II} – calculated mass of Type 2 fraction, kg; $X_{i\,II}$ – actual (measured) value of the i-th parameter of Type 2 fraction; M_G – calculated mass of the grain mechanical cleaning waste, kg; $X_{i\,G}$ – actual (measured) value of the i-th parameter of the grain mechanical cleaning waste; M_W – calculated mass of water, kg; $X_{i\,W}$ – actual (measured) value of the i-th parameter of water; M_B – calculated mass of BIAGUM organic fertiliser, kg; $X_{i\,B}$ – actual (measured) value of the i-th parameter of BIAGUM organic fertiliser.

The optimal composition was chosen among the set of Pareto-optimal solutions.

The experiments were carried out in the laboratory of the organic waste bioconversion of IEEP – branch of FSAC VIM, the analyses – in the analytical laboratory of the same institute in February – April 2019. The experiments had three replications.

Two types of the solid fraction of pig slurry were the starting material for the accelerated processing: Type 1 fraction – coming from a screw separator, and Type 2 fraction – coming from a decanter centrifuge. The initial values of physical and chemical composition of the native pig slurry were the same since the considered separation technology variants were applied on the same pig-rearing complex of the full cycle, located in the North-West Russia.

The study subject was the accelerated processing of Type 1 and Type 2 fractions in the express-fermenter. The fermenter had the volume of 0.8 m^3 that provided the minimal critical mass required for the successful process of the solid-state aerobic fermentation. The installation was a closed chamber with the aeration holes in the bottom. The installed mixer simulated the controlled fermentation in the stationary operating mode and the regular mixing mode. The scheme of the laboratory-scale express-fermenter is shown on Fig. 1. The RK-102-10-50 compressor supplied the air.



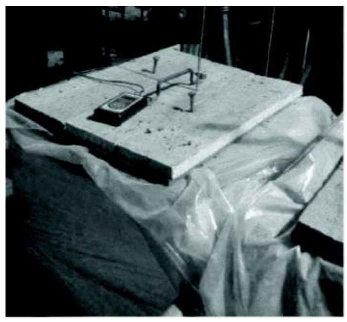


Figure 1. Laboratory-scale express-fermenter: 1 – chamber; 2 – loose cover; 3 – perforated plate; 4 – aeration pipe; 5 – air inlet; 6 – mixer; 7 – free handle; 8 – plugs; 9 – temperature measurement holes.

According to our previous studies, the key factor to successful solid-state aerobic fermentation was to maintain a stable temperature in the range of 55–80 °C that ensured the maximum activity of the thermophilic microorganisms (Manure Composting Manual, 2005).

The calibrated equipment was used in the experiment: the ambient temperature was measured by an inside air thermometer TS-77; the temperature inside the express-fermenter was measured by TCM 9410/M2 thermometer with a thermal probe. The physical and chemical properties of the processed material were determined following the relevant State Standards:

- State Standard GOST 26713-85. ‘Organic fertilisers. Method for determination of moisture and dry residue’;
- State Standard GOST 26714-85. ‘Organic fertilisers. Method for determination of ash content’;
- State Standard GOST 26715-85. ‘Organic fertilisers. Methods for determination of total nitrogen’;
- State Standard GOST 26716-85. ‘Organic fertilisers. Methods for determination of ammonium nitrogen’;
- State Standard GOST 26717-85. ‘Organic fertilisers. Method for determination of total phosphorus’;
- State Standard GOST 26718-85. ‘Organic fertilisers. Method for determination of total potassium’;
- State Standard GOST 27979-88. ‘Organic fertilisers. pH determination method’;
- State Standard GOST 27980-88. ‘Organic fertilisers. Organic substance determination methods’.

The sampling followed the State Standard GOST R 54519-2011. ‘Organic fertilisers. Methods of sampling’.

The express-fermenter operating modes were tested in the previous studies associated with the processing of the solid fraction of cattle manure and the bedding poultry manure – Table 1 (Uvarov et al., 2016; Uvarov et al., 2017a; Uvarov et al., 2017b).

The experimental data was statistically analysed in *StatGraphics Centurion v.16.1* software package.

Table 1. Variation levels of the controlled factors

Parameter	Unit	Mode I	Mode II	Mode III
Aeration time	min h^{-1}	20	13	7
Aeration speed	m s^{-1}	10	7.5	5.5
Mixing interval	h	24	18	12

RESULTS AND DISCUSSION

Step 1

Fermentation process was affected by several factors, such as moisture content, C/N ratio, pH and the physical and chemical properties of the starting materials (Manure Composting Manual, 2005; Takahashi et al., 2017). These indicators were determined by the laboratory analyses – Table 2.

The variation of the material moisture content was below 5%, with the values being in the upper acceptable recommended range. The pH values varied significantly. Type 2 fraction was 4.1 units more alkaline and had a significantly higher ash content (45.4%) than Type 1 fraction with a pH of 7.9and the ash content

Table 2. Physical and chemical properties of the starting materials

Indicator	Unit	Type 1 fraction	Type 2 fraction
Moisture content (W)	%	70.59	67.36
pH	-	7.9	12.0
NH_4^+	mg kg^{-1}	464.0	62.9
NO_3^-	mg kg^{-1}	118.1	947.1
K^+	mg kg^{-1}	495.0	479.0
P_{total}	mg kg^{-1}	2,000.0	8,100.0
N_{total}	mg kg^{-1}	5,370.0	8,148.0
Ash content	%	6.4	45.4

of 6.4% since during the on-farm processing of this waste the quicklime (CaO) was added. Thus launched nitrification processes also significantly reduced ammonium nitrogen (NH_4^+) content and increased the nitrate nitrogen (NO_3^-) content.

The starting materials were loaded simultaneously in two laboratory-scale express-fermenters (Fig. 2).

Figure 2. Trial establishment: a) laboratory-scale express-fermenters; b) solid fraction of pig slurry coming from the screw separator (Type 1 fraction); c) solid fraction of pig slurry coming from the decanter centrifuge (Type 2 fraction).

The ambient conditions were the same for the two express-fermenters. The average air temperature inside the laboratory was 12 ± 1 °C. The temperature in the express fermenters was recorded once a day for nine days (Fig. 3) since in the similar studies of other types of organic waste this particular experiment duration and measurement frequency were found optimal (Uvarov et al., 2016; Briukhanov & Uvarov, 2016; Uvarov et al., 2017b).

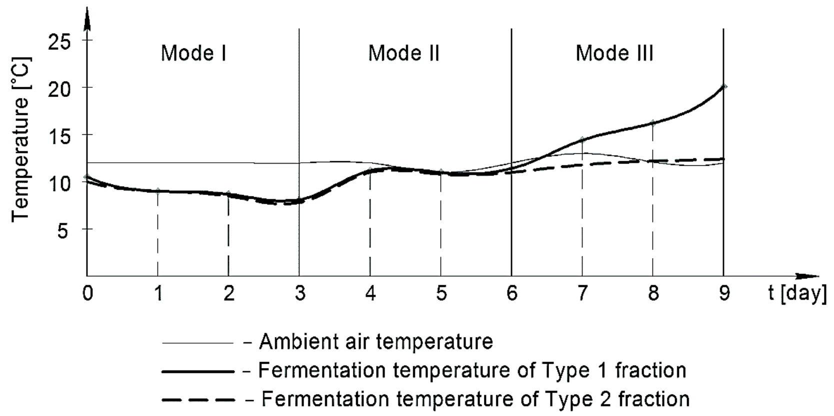


Figure 3. The temperature under the different operating modes of the express-fermenters (Stage 1).

The experiments established that the temperature of 55 °C to 80 °C, required for the stable activity of thermophilic microorganisms, was not reached under the considered operating modes. The fermentation process did not enter the mesophilic phase either, when the decomposition of complex carbohydrates, amino acids, and lignin began. The alkaline environment in Type 2 fraction inhibited the activity of microorganisms and did not allow reaching the fermentation temperature above 12.5 °C, while the maximum value achieved in Type 1 fraction was 20.1 °C.

Analysis of Type 2 fraction revealed its high alkalinity. Considering that the main aim of fermentation is to disinfect the slurry from the pathogenic microflora and weed seeds, it can be assumed that the alkaline medium observed in this material (pH = 12) is not favorable for pathogens and parasites, and does not contribute to weed seeds germination. In case they are not found, this type of organic waste can be dried and used as an organic fertiliser for acidic soils, as it has a potential reclamation effect. This assumption, however, needs further examination.

Since the considered operating modes of the express-fermenters in the previous studies proved to be effective, the need to change the physical and chemical composition of the fermented material was assumed.

The analysis of the physicochemical composition of Type 1 and Type 2 fractions showed the C/N ratio not to correspond to the optimal values of (20…30)/1 (Manure Composting Manual, 2005; MDAIC 1.10.15.02-17, 2017). Following the reported experience (Huang, 2004; Chen, 2005), the carbon-containing components were added to the solid fraction of pig slurry to be processed.

Step 2

Based on Step 1 outcomes, the decision was to change the composition of the processed material by adding the grain mechanical cleaning waste and BIAGUM organic fertiliser, a fermented bedding poultry manure. The physical and chemical properties of the starting components were determined in the laboratory analysis – Table 3.

Table 3. Physical and chemical properties of the starting materials

Indicator	Unit	Type 1 fraction	Type 2 fraction	Grain mechanical cleaning waste	BIAGUM organic fertiliser
Moisture content (*W*)	%	71.26	66.86	13.86	62.2
pH	-	8.0	12.0	6.9	8.5
NH_4^+	mg kg^{-1}	443.0	61.4	167.0	2,770.0
NO_3^-	mg kg^{-1}	117.5	921.5	47.2	890.0
K^+	mg kg^{-1}	492.0	473.0	1,373.0	2,890.0
P_{total}	mg kg^{-1}	2,000.0	8,100.0	3,300.0	4,970.0
N_{total}	mg kg^{-1}	5,320.0	8,128.0	1,036.0	20,500.0
Ash content	%	6.4	45.3	12.5	19.2

The composition of the test samples of the substrate to be fermented was determined by the results of physical and chemical analysis of the starting materials – Table 4.

The samples were prepared and loaded in the express-fermenters simultaneously. The ambient conditions were the same for the two express-fermenters. The average air temperature inside the laboratory was 12 ± 1 °C. The temperature in the express fermenters was recorded once a day for nine days (Fig. 4) as in the experiment on Step 1 of the study.

Table 4. Quantitative composition of the tested samples of the substrate

Component	Sample 1		Sample 2	
	kg	%	kg	%
Type 1 fraction	24.40	45.6	28.403	52.5
Type 2 fraction	14.34	26.8	17.961	33.2
Grain mechanical cleaning waste	3.58	6.7	4.003	7.4
Water	2.78	5.2	3.733	6.9
BIAGUM organic fertiliser	8.35	15.6	-	-
TOTAL	53.5	100	54.1	100

The experiment demonstrated that under the considered operating modes the temperature from 20 °C to 55 °C, required for the stable activity of mesophilic microorganisms, was achieved and remained stable. A periodic transition to the thermophilic phase under the temperature above 55 °C was also observed. A factor limiting the further temperature increase was, presumably, a small mass of the substrate. Testing of the considered operating modes under the bigger mass of the substrate, starting, for example, with 500 kg, might verify this assumption.

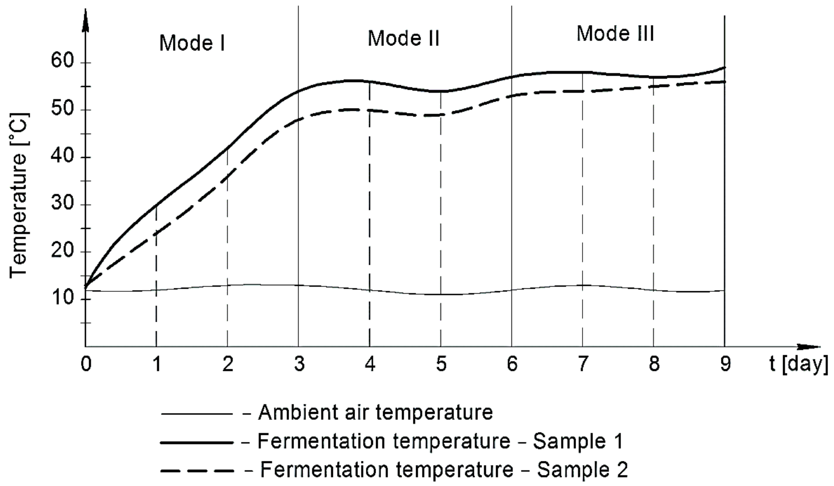


Figure 4. The temperature under different operating modes of the express-fermenters (Stage 2 of the study).

Mixing Type 1 fraction, Type 2 fraction and the grain mechanical cleaning waste had a positive effect on the physical and chemical composition of the processed substrate making it more suitable for the solid-state aerobic fermentation. The addition of BIAGUM organic fertiliser to Sample 1 contributed to a more intense dynamics of temperature increase. Under Mode I, the temperature difference of the substrates was about 6 °C (12–25%) that was primarily associated with the temperature increase; under Mode III, when the temperature in the express fermenters stabilised, this indicator reached 2–4 °C (3.5–7%).

With this in mind, it is acceptable to assert the feasibility of using BIAGUM fertiliser, or similar, as a starting catalyst for the process of solid-state aerobic fermentation.

The study findings support the general viewpoint concerning the feasibility of pig slurry separating into fractions for its more efficient processing (Hjorth, 2010; Hou, 2018). However, aerobic fermentation or composting of the solid fraction is difficult due to its non-optimal chemical composition. Adding lignin-rich substances to the processed substrate can even the C/N balance and contribute to the onset of fermentation processes owing to the activity of mesophilic and thermophilic microorganisms (Uao, 1993; Huang, 2004). With this in mind, it is acceptable to assert the feasibility of using the fermented poultry manure, or similar, as a starting catalyst for the process of solid-state aerobic fermentation (Uvarov, 2016; Onwosi, 2017).

CONCLUSIONS

According to the previously conducted studies, the fermentation of the solid fraction of pig slurry presented certain challenges due to the physical and chemical properties of the processed material. The direction of further research was to identify the quantitative and qualitative composition of the mixture required for the successful fermentation process.

The experiments verified that the mix of the solid fraction of pig slurry coming from the screw separator – Type 1 fraction (45.6–52.5% of the total volume), the solid fraction of pig slurry coming from the decanter centrifuge – Type 2 fraction (26.8–33.2% of the total volume), grain mechanical cleaning waste (6.7–7.4% of the total volume) and water (5.2–6.9% of the total volume) ensured the normal course of the fermentation process.

The catalyzing components, for example, BIAGUM organic fertiliser, produced from the bedding poultry manure, added to the substrate at its preparation stage, accelerated the substrate self-heating and allowed to reach a higher temperature – up to 59°C. However, when the fermentation process passed to the thermophilic phase, this difference was insignificant (2–4 °C).

At this stage of study, it is too early to speak about the advantages of a certain operating mode of the fermenter. For example, Mode I (aeration time – 20 min h^{-1}; aeration speed – 10 m s^{-1}; mixing interval – 24 hours), featured the lowest average temperature inside the express fermenters but the highest dynamics of its increase. Mode II (aeration time – 13 min h^{-1}; aeration speed – 7.5 m s^{-1}; mixing interval – 18 h) and Mode III (aeration time – 7 min h^{-1}; aeration speed – 5.5 m s^{-1}; mixing interval – 12 h) had a similar dynamics of temperature increase – it stabilised in the range of 50 °C to 55 °C but periodically exceeded this range, with the fermentation process passing to the thermophilic phase. Optimisation of the operating modes of fermentation installations when processing the solid fraction of pig slurry is an area of further research.

The study outcomes allow concluding that the solid-state aerobic fermentation is one of the promising options for the utilization of the solid fraction of pig slurry.

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